International Journal of Mechanical and Production
Engineering Research and Development (IJMPERD)
ISSN(P): 2249–6890; ISSN(E): 2249–8001
Vol. 10, Issue 1, Feb 2020, 489–498

OPTIMIZATION OF CUTTING PARAMETERS IN HARD TURNING OF AISI O1 STEEL USING PVD TiAlN COATED CARBIDE INSERT

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ABSTRACT

Modern industries are trending towards the environmentally friendly and economical way of machining. Also, it has become requisite in turning hard materials to replace the time-consuming conventional machining methods with quicker machining techniques. The present work investigates the surface roughness and tool wear of AISI O1 steel in hard turning with dry, wet and minimum quantity lubrication (MQL) conditions. The experiment was carried out using PVD-TiAlN coated carbide insert. Varying cutting speeds and feeds are used in machining keeping constant depth of cut. The results substantiated the application of MQL in hard turning with good surface finish and tool wear compared to the dry and wet conditions. Analysis of Variance (ANOVA) is carried out to fix the most significant parameters. The most desirable parameters for attaining optimum surface finish and tool wear are selected using grey relational analysis (GRA).

***KEYWORDS:** Analysis of Variance (ANOVA), Grey Relational Analysis (GRA), Hard Turning, PVD Coated Carbide Insert and Surface Roughness & Tool Wear*

Received: Nov 06, 2019; **Accepted:** Nov 26, 2019; **Published:** Jan 28, 2020; **Paper Id.:** IJMPERDFEB202040

Original Article

Abbreviations

AISI	American Iron and Steel Institute
CBN	Cubic boron nitride
CNC	Computer numerical control
HRC	Rockwell hardness 'C' scale
MS	Mean square
SR	Surface roughness
TW	Tool wear
ANOVA	Analysis of variance
CF	Cutting fluid
DOF	Degrees of freedom
GRA	Grey relational analysis
HT	Hard turning
OHNS	Oil hardened non-shrinkable steel
SS	Sum of square

INTRODUCTION

Recent developments in machining of hard materials replaced the traditional tedious process of grinding the hard materials to the required finish with easier hard turning (HT)process. Hard turning not only minimized the cost and time of production [1-4], also removed the barrier of restricting the geometry of the work piece. Hard turning reduces setup time, increases the surface finish, work piece removal rate, flexibility in design and avoids

environmental problems [5,6]. Moreover, the cutting fluids (CFs)used in traditional wet process causes skin and respiratory problems to workers [7, 8] and stern environmental pollution [9, 10]. Due to the increase in global awareness and compulsion to use the environmentally friendly machining, industries look forward to the effective use of environmentally friendly machining conditions. As a result, the concept of green machining such as dry machining, minimum quantity lubrication(MQL), compressed air cooling, cryogenic cooling etc., gained more importance. Researches on using vegetable oil instead of conventional mineral oil as cutting fluid have attained global importance. To uphold eco-friendly environment, MQL using vegetable oil has developed as an efficient, economical and safe technique by minimizing the usage of CFs[11]. Vegetable based biodegradable CFs are renewable, less toxic, environmentally friendly and also sustainable [12].

Hard turning involves in machining of materials above 45HRC and hence requires hard tool material with less wear capability. With new development in tool materials, coated ceramic [13-15], coated carbide tools [16-18], cubic boron nitride(CBN)[19, 20] and polycrystalline cubic boron nitride(PCBN) [21-22] are used by researchers for HT.

The growing demands of the manufacturing sectors for higher quality and dimensional accuracy of the machined parts necessitates producing components with good surface finish. Also, surface roughness (SR) plays a vital role by influencing machined components wear rate, fatigue strength, corrosion resistance and coefficient of friction [23]. One of the dominant factors affecting surface finish is tool wear (TW), as it also influences the dimensional accuracy of the parts. J. P. Davim and L. Figueira investigated turning of cold work tool steel with ceramic insert and concluded that SR can be contained well below 0.8μm with the application of appropriate cutting parameters [24]. V. Sivaraman and S. Prakash carried out experiments in HT of OHNS with ceramic tool in wet condition and found feed rate as the dominating parameter [25]. G. C. Benga & A. M. Abrao conducted experiments with various tool materials in turning of hardened bearing steel and found that feed as the major factor influencing SR irrespective of tool material used [26]. They also found that cutting speed influenced the TW irrespective of the tool material used R. Suresh et al in their study used coated carbide insert in turning of hardened AISI 4340 steel and established that cutting speed influenced TW mostly followed by feed rate and depth of cut [27]. N. R. Dhar et al. compared MQL turning with dry and conventional wet turning and suggested that MQL resulted in improved SR and less TW [28].

Research work has been done in HT of various hard materials, but only few works are done in HT of AISI O1 steel. In this study experiments on turning of oil hardened AISI O1 tool steel under conventional (wet) and environmentally friendly (Dry and MQL) conditions are conducted with Taguchi's L27 orthogonal array. Significant factors for SR and TW are identified and the optimal cutting parameters for reduced TW and SR are selected using grey relational analysis (GRA).

2. EXPERIMENTAL STUDIES

2.1 Work Piece

Oil hardened AISI O1 cold worked tool steel, also called as oil hardened non-shrinkable steel(OHNS) is used in gauges, tools, dies, punches etc. Table 1 gives the chemical composition of AISI O1 tool steel. The work pieces are oil hardened up to 62 HRC. Work piece of size Ø30 x 50 mm is used for the experimentation.

Table 1: Chemical Composition of AISI O1 Tool Steel

Elements	C	Mn	Si	Cr	Ni	W	V	Cu	P	S	Fe
Weight (%)	0.85 – 1.00	1.00 – 1.40	0.50	0.40– 0.60	0.30	0.40 – 0.60	0.30	0.25	0.03	0.03	Balance

2.2 Tool

PVD-TiAlN coated carbide insert with ISO designation CNMG 120408 (KORLOY make) clamped mechanically on PCLNR 2525M12 tool holder is used for the experimentation.

2.3 MQL

A MQL set up consisting of a reservoir, filter and regulator unit with pressure gauge and a nozzle is used to dispense cutting fluid in the form of mist at the required pressure and flow rate. Castor oil is used as coolant in the MQL system.

2.4 Surface Roughness

Surface roughness is measured using MITUTOYO make Surftest201. Measurements are taken at three points 120 degrees apart with 8 mm cut-off length and the average value is used for the analysis.

2.5 Tool Wear

The inserts are measured for flank wear (FW) after the turning operation for each set of experiment conditions. Video Measuring device (VMS-1020F) is used to measure the tool FW.

3. DESIGN OF EXPERIMENTS

Three factors, environment (cooling) condition, cutting speed and feed are considered in this experiment with three levels for each factor. Table 2 represents the various levels for these factors. Taguchi's L27 orthogonal array is selected for experimentation. The experiment results are given in table 3. The experiment is conducted in dry condition by turning off the coolant supply, and wet condition with commercial cutting fluid and a specially designed MQL system with castor oil is supplied in the form of mist at a pressure of 2.5 bar and flow rate of 70 ml/hr. The viscosity of castor oil is 0.535 Pa. s.

Table 2: Control Parameters for Turning Experiment

Factors	Level 1	Level 2	Level 3
Environment condition	Dry	Wet	MQL(Castor oil)
Cutting Speed(m/min)	110	140	170
Feed rate(mm/rev)	0.02	0.05	0.08
Depth of cut(doc) (mm)	0.7	0.7	0.7

4. RESULTS AND DISCUSSIONS

Surface roughness and FW of each experimental condition are tabled in table 3. The SR recorded varies from a minimum value of 0.36μm to a maximum value of 1.21 μm. The FW varies from a minimum value of 0.115 mm to a maximum value of 0.221 mm.

Table 3: Experimental Results for Surface Roughness (Ra) and Flank Wear (Vb)

Sl. No.	Environmental Condition	Cutting Speed (V) m / min	Feed (f) mm / rev	Surface Roughness (Ra) μm	Tool Wear (Vb) mm
1	D	110	0.02	0.75	0.152
2	D	110	0.05	0.84	0.168
3	D	110	0.08	1.21	0.186
4	D	140	0.02	0.71	0.161
5	D	140	0.05	0.8	0.183
6	D	140	0.08	0.94	0.208
7	D	170	0.02	0.68	0.198
8	D	170	0.05	0.78	0.206
9	D	170	0.08	0.86	0.221
10	W	110	0.02	0.57	0.134

11	W	110	0.05	0.7	0.152
12	W	110	0.08	0.79	0.177
13	W	140	0.02	0.54	0.151
14	W	140	0.05	0.65	0.168
15	W	140	0.08	0.73	0.183
16	W	170	0.02	0.48	0.169
17	W	170	0.05	0.61	0.189
18	W	170	0.08	0.68	0.201
19	M	110	0.02	0.48	0.115
20	M	110	0.05	0.56	0.127
21	M	110	0.08	0.68	0.141
22	M	140	0.02	0.39	0.131
23	M	140	0.05	0.48	0.142
24	M	140	0.08	0.64	0.157
25	M	170	0.02	0.36	0.151
26	M	170	0.05	0.52	0.164
27	M	170	0.08	0.63	0.181

4.1 Surface Roughness (SR)

The variations of SR with respect to cutting speed at different feed under various environmental conditions dry, wet and MQL are shown Figure 1. Cooling environment condition affects the surface roughness values more followed by feed and cutting velocity. At higher speeds, the SR decreases and vice versa. Minimum SR recorded when the cutting velocity is maximum (170 m / min), and maximum SR is recorded at minimum speed (110 m / min). The effect of SR with respect to feed under various environmental conditions dry, wet and MQL are shown in Figure 2. Surface roughness increases with increase in feed, maximum surface roughness is recorded at higher feed (f = 0.08 mm/min) and minimum surface roughness is recorded at lowest feed (f = 0.02 mm/rev). Improvement in surface finish in MQL condition is due to the reduction in cutting temperature, removal of chips and reduction in TW.

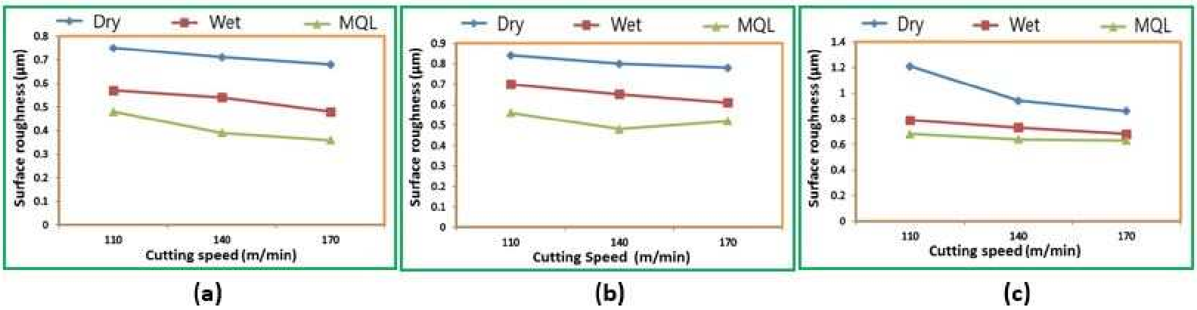

Figure 1: Surface Roughness Vs Cutting Speed at Constant doc = 0.7 mm (a)f = 0.02 mm/rev (b)f = 0.05 mm/rev (c) f = 0.08 mm/rev

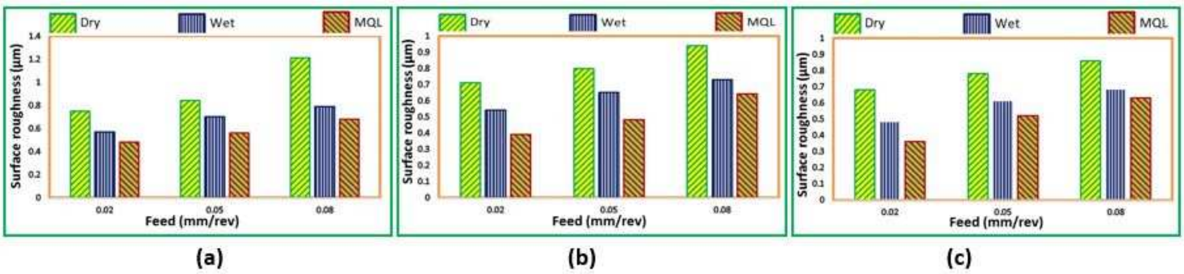

Figure 2: Surface Roughness Vs Feed at Constant doc = 0.7 mm (a) V = 110 m/min (b) V = 140 m/min (c) V = 170 m/min

4.2 Tool Wear (TW)

The life of tool holds key role in controlling manufacturing cost. Failure of turning tools may happen due to brittle nature of the tool, plastic deformation or gradual wear. Carbide inserts have enough strength, toughness and generally fail due to gradual wear. Crater wear occurring at rake face and flank wear occurring at clearance face are the common types of tool wear in turning. Generally, FW is taken as criteria for defining tool life[29]. During turning, FW increases with increase in cutting speed and feed. The amount of FW against various cutting speed at different feed under various environmental conditions dry, wet and MQL are shown in the Figure 3. Minimum FW recorded at minimum speed (110 m/min) and MQL condition. The variations in FW with feed rate at different cutting speed and environmental conditions are shown in Figure 4. FW increases with increase in feed and minimum FW is recorded at least feed (0.02 mm/rev) and MQL condition. The better cooling and lubricating effect due to mist spray at the tool-chip interface resulted in minimum TW.

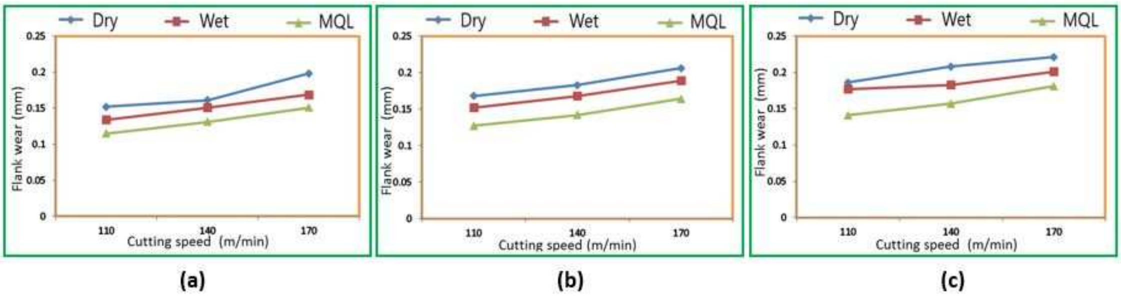

Figure 3: Flank Wear Vs Cutting Speed at Constant doc = 0.07 mm(a) f = 0.02 mm/rev (b) f = 0.05 mm/rev (c) f = 0.08 mm/rev

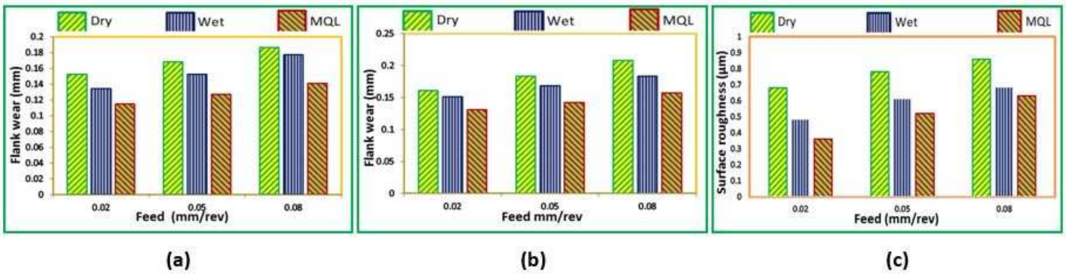

Figure 4: Flank Wear Vs Feed at Constant doc = 0.07 mm(a) V = 110 m/min (b) V = 140 m/min (c) V = 170 m/min at doc = 0.07 mm

4.3 Analysis of Variance (ANOVA)

The results of ANOVA for SR are shown in the Table 4. The most significant factor influencing SR is the environment condition, followed by feed rate and cutting velocity. Environment condition contributed 54.65%, followed by feed 32.27% and cutting speed 6.77%.

Table 4: ANOVA for Surface Roughness (Ra)

Source	SS	DOF	MS	F(cal)	F –Value	% Contribution	Conclusion
Environment Condition	0.457089	2	0.228544	86.57	3.49	54.65	Significant
Cutting Speed	0.056622	2	0.028311	10.72	3.49	6.77	Significant
Feed	0.269956	2	0.134978	51.13	3.49	32.27	Significant
Error	0.052800	20	0.002640				
Total	0.836467	26					

The results of ANOVA for TW are shown in the Table 5. ANOVA calculations for the TW indicate that

environment condition is the most significant factor followed by cutting speed and feed. Environment condition, cutting velocity and feed rate contributes 41.23%, 31.87% and25.15%, respectively. Lower cutting velocity 110 m / min and minimum feed 0.02 mm/rev recorded the minimum flank wear 0.115 mm. Cutting velocity 170 m/min, feed 0.08 mm and dry turning recorded maximum flank wear of 0.221 mm

Table 5: ANOVA for Tool Wear (Vb)

Source	SS	DOF	MS	F(cal)	F –Value	% Contribution	Conclusion
Environment condition	0.007829	2	0.003914	236.23	3.49	41.23	Significant
Cutting speed	0.006053	2	0.003026	182.64	3.49	31.87	Significant
Feed	0.004776	2	0.002388	144.11	3.49	25.15	Significant
Error	0.000331	20	0.000017				
Total	**0.018989**	**26**					

4.4 Grey Relational Analysis (GRA)

Data obtained from the sources or experiments are often vague and unclear. This unclear information is transformed to clear and complete information using grey relational analysis. Grey relational analysis transfer the black (no information) to grey(less information), and then transfer the grey information to white(full information). The results of GRA are tabulated in the table 6.

- GRGC – Grey relational generation calculation.
- DSGC – Deviation sequence generation calculation.
- GRCC – Grey relational co-efficient calculation.
- GRG – Grey relational grade calculation.

Table 6: Grey Relational Calculation

Sl. No.	GRGC		RSDC		GRCC		GRG	RANK
	Ra	TW	Ra	TW	Ra	TW		
Reference Sequence(Xo)	**1.0000**	**1.0000**	**1.0000**	**1.0000**	**1.0000**	**1.0000**		
1	0.5412	0.8214	0.4588	0.1786	0.5215	0.7368	0.6292	10
2	0.4353	0.6607	0.5647	0.3393	0.4696	0.5957	0.5327	17
3	0.0000	0.4107	1.0000	0.5893	0.3333	0.4590	0.3962	27
4	0.5882	0.6786	0.4118	0.3214	0.5484	0.6087	0.5785	15
5	0.4824	0.4911	0.5176	0.5089	0.4913	0.4956	0.4935	22
6	0.3176	0.2589	0.6824	0.7411	0.4229	0.4029	0.4129	25
7	0.6235	0.3839	0.3765	0.6161	0.5705	0.4480	0.5092	20
8	0.5059	0.2679	0.4941	0.7321	0.5030	0.4058	0.4544	24
9	0.4118	0.0000	0.5882	1.0000	0.4595	0.3333	0.3964	26
10	0.7529	0.9196	0.2471	0.0804	0.6693	0.8615	0.7654	4
11	0.6000	0.7768	0.4000	0.2232	0.5556	0.6914	0.6235	11
12	0.4941	0.5536	0.5059	0.4464	0.4971	0.5283	0.5127	19
13	0.7882	0.7768	0.2118	0.2232	0.7025	0.6914	0.6969	7
14	0.6588	0.6429	0.3412	0.3571	0.5944	0.5833	0.5889	14
15	0.5647	0.4286	0.4353	0.5714	0.5346	0.4667	0.5006	21
16	0.8588	0.5804	0.1412	0.4196	0.7798	0.5437	0.6618	9
17	0.7059	0.3393	0.2941	0.6607	0.6296	0.4308	0.5302	18
18	0.5882	0.2321	0.4118	0.7679	0.5484	0.3944	0.4714	23
19	0.8588	1.0000	0.1412	0.0000	0.7798	1.0000	0.8899	2
20	0.7294	0.8929	0.2706	0.1071	0.6489	0.8235	0.7362	5
21	0.5882	0.7679	0.4118	0.2321	0.5484	0.6829	0.6157	12
22	0.9647	0.9196	0.0353	0.0804	0.9341	0.8615	0.8978	1

23	0.8588	0.7589	0.1412	0.2411	0.7798	0.6747	0.7273	6
24	0.7059	0.6250	0.2941	0.3750	0.6296	0.5714	0.6005	13
25	1.0000	0.6786	0.0000	0.3214	1.0000	0.6087	0.8043	3
26	0.8941	0.5893	0.1059	0.4107	0.8252	0.5490	0.6871	8
27	0.7765	0.4018	0.2235	0.5982	0.6911	0.4553	0.5732	16

Table7: Response Table for Grey Relational Grade

Level	Environment condition	Cutting speed	Feed
1	0.489211	0.633481	0.714786
2	0.59459	0.610765	0.597068
3	0.725777	0.565332	0.497723
Delta	0.236567	0.068149	0.217064
Rank	1	3	2

From the response table shown in table 7, environment condition is the most important factor followed by feed rate and cutting speed. Optimum result is obtained when the experiment is run at A3B1C1 condition i.e., MQL, V = 110 m/min and f = 0.02 mm/rev.

5. CONFIRMATION TEST

Confirmation test with optimal parameters cutting speed 110 m/min, feed 0.02 mm/rev and MQL condition is conducted. The work piece is measured for surface roughness and insert is measured for TW. SR measured as 0.49 µm and FW measured as 0.119 mm. The results confirmed that optimum values are attained with the selected parameters.

6. CONCLUSIONS

Oil hardened AISI O1 tool steel is turned using PVD-TiAlN coated carbide insert in dry, wet and MQL conditions. ANOVA test is carried out to find the significant factors, and grey relational analysis is used to find the cutting parameters for optimum surface finish and TW. The following conclusions are made.

- Environment (cooling) condition is the most significant factor influencing SR followed by feed and cutting velocity.
- Environment conditions contributed 54.65% followed by feed 32.27% and cutting speed 6.77% for the SR.
- Dry condition produced maximum SR and MQL resulted in minimum SR.
- Surface roughness increased with increase in feed and minimum SR recorded at minimum feed.
- Increase in cutting speed resulted in decrease of SR and lowering cutting speed increases the SR value.
- Environment condition (41.23%) is the most important factor influencing TW followed by cutting speed (31.87%) and feed (25.15%).
- MQL produced minimum TW while maximum TW occurred in dry condition.
- Tool wear increased with increase in feed and cutting speed.
- From GRA, optimum values of SR and TW are obtained at MQL, cutting speed 110 m/min and feed 0.02 mm/rev.

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